NASA CONTRACTOR REPORT

NASA CR-61079

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APOLLO EXTENSION SYSTEM PAYLOADS MANNED FLYING SYSTEM (MFS) KINESTHETIC EFFECTS

Prepared under Contract No. NAS8-20082 by

D. W. Thomas

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6025 Technology Drive
Huntsville, Alabama

For

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

June 1965

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SYSTEMS CONCEPTS PLANNING OFFICE
AERO-ASTRODYNAMICS LABORATORY

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

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PREFACE

This report presents an analysis of the kinesthetic effects of astronaut movements on the cg of the Lunar Flying Vehicle (LFV). The report was prepared by the Northrop Space Laboratories (NSL), Huntsville Department, for the George C. Marshall Space Flight Center. The technical work was accomplished under the Scope of Work for Schedule Order No. 4, Appendix F-1, Contract NAS8-20082. Technical Directive No. 3 provided specific requirements for performance of the task for which approximately 8 man weeks of effort were expended.

The NASA Technical Coordinator was Mr. Lynn Bradford of the MSFC Aero-Astrodynamics Laboratory.

SECTION 1.0

INTRODUCTION

The report represents the results of a cursory examination of the kinesthetic effects of a lunar flying vehicle. This is of particular importance during the terminal phase of the flight, when the ratio of the astronaut weight to vehicle weight approaches unity. The results presented herein represent the gross steady state effects of cg shift in the astronauts and no attempt was made to study the dynamical effects associated with astronaut body movements.

The configuration of the LFV was as presented in the Bell Aerosystems Company mid-term presentation entitled "Study of Lunar Flying Vehicles", dated February 1965. Specific assumptions pertinent to this investigation are listed below:

(1) The thrust direction of the engine cluster is fixed and acts through the nominal cg of the vehicle and astronauts.

(2) Two astronauts are on the vehicle, each equippped with the Apollo backpack, plus helmet and communications gear.

(3) Attitude control is achieved by reaction jets placed to operate in pairs, and mounted at the four corners of the vehicle.

(4) The astronauts are assumed to be strapped to the seat, thus only upper body motion and arm motion is to be considered. Further, the backpack limits the posteriol movement of the body.

(5) The thrust vector acts through the nominal cg of man in a seated position with seat 90° to back, with both arms down at sides, with astronauts in full space suits and backpacks.

(6) The vehicle's cg is assumed to remain on the thrust axis, thus this study is confined to the effects of body motion.

(7) The cg of the astronaut in a space suit remains along the centerline of the man; that is, all weight is symmetrical about the body center.

SECTION 2.0

GENERAL

A free body force diagram for the lunar flying vehicle situation considered in this report is shown in Figure 1. The forces considered are the Thrust, T, the astronaut's weight, Wa, and the reaction thrust, R, and the vehicle's weight, Wv.

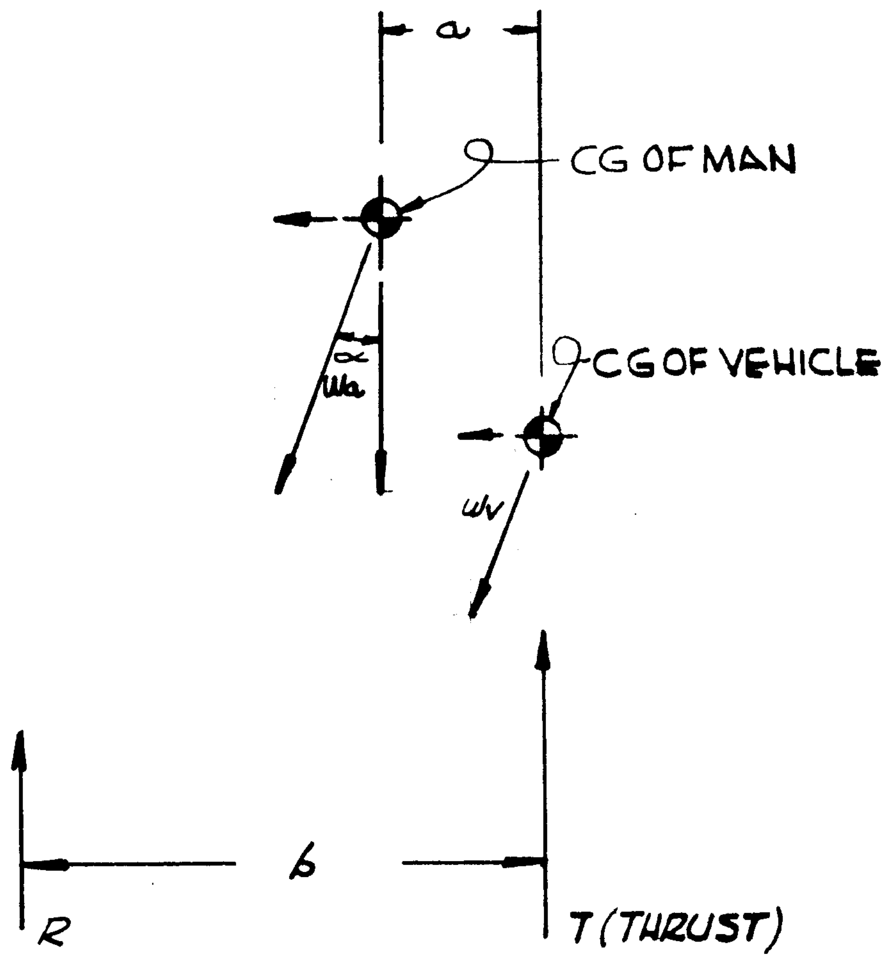
In the ideal case, the cg of the astronauts and the vehicle will lie on the action line of the thrust, T. Various factors will tend to relocate the vehicle cg and the astronaut cg off the thrust axis. This will result in an overturning moment on the vehicle. To maintain the vehicle in equilibrium, reaction jets are typically used to generate an equal and opposite moment.

Referring to Figure 1, the moments are taken about the axis of thrust. It is assumed that the vehicle cg remains unperturbed from the thrust axis, thus the vehicle weight does not generate an overturning moment. The astronauts are assumed to displace their cg due to body motion. For a particular axis the shift in the cg may be represented by the distance, a.

Displacement of the cg is considered along two of the three vehicle axis. The distance, a_r, represents displacement along the roll axis of the vehicle. This displacement is caused by forward motion of the astronauts' bodies and results in an overturning moment about the pitch axis.

The distance, a_p, represents displacement of the cg along the pitch axis. This displacement is caused by lateral motion of the body and results in an overturning moment about the roll axis of the vehicle.

The third axis is the yaw axis. Displacements along this axis do not affect the stability of the vehicle since overturning moments are not generated. Displacement of the cg along the yaw axis of the vehicle would be caused by raising both arms and/or legs. The effect of these movements is not considered.



FREE BODY FORCE DIAGRAM OF LUNAR FLYING VEHICLE

FIGURE 1

SECTION 3.0

BACKGROUND DATA ON CG SHIFT IN MAN

A considerable amount of work has been done in relation to the study of the centers of gravity of man. References (2) and (3) represent a portion of this work. The following data was obtained from these reports and is included as background information for this study.

The reference point for measurement of the cg along the roll axis is the back of the astronaut. This is not in contact with the seat back because of the backpack. The reference point for lateral cg shifts, that is along the pitch axis of the vehicle, is the centerline of the man.

3.1 CG DISPLACEMENTS ALONG ROLL AXIS

Tables 1, 2, and 3, provide data taken on 27 subjects ranging in stature from 61 inches to 74 inches, in weight from 118 lbs to 224 lbs, and in age from 24 to 57 years (Reference 3). Despite the wide variation in subjects the centers of gravity fell within limited ranges, as indicated in the tables.

From a review of these tables we can see that the cg of the man cannot be shifted greater than 1 1/2 inches merely by movement of the arms, either singley or in pairs. By flexing the trunk forward, the greatest displacement occurred, that is 6 3/4 inches. It should be noted however that this body motion was rather severe in that the subjects were endeavoring to maximize the shift. Such motions as these would not be possible in a space suit.

3.2 CG DISPLACEMENT ALONG PITCH AXIS

Table 4 represents the only data available in the reports concerning the cg shifts by lateral movements of the body. It is noted that the subject in these tests were standing. This however does not invalidate the data with regard to the lateral shift accompanied by movements of the arms or upper portion of the body.

TABLE 1

POSITION OF MAN'S CG ALONG ROLL AXIS FOR VARIOUS BODY POSITIONS (SITTING WITH SEAT 90° TO BACK, LEGS 90° TO THIGHS)

	Body Position	Location of Av. C. G. (Inches)	Horizontal Range For Subjects (Inches)
A.	Both arms down at sides	8-3/8	$\pm$ 7/8
B.	Both hands in lap	8-7/8	$\pm$ 7/8
C.	One arm forward, one hand in lap	9-1/4	$\pm$ 5/8
D.	Both arms straight forward	9-3/4	$\pm$ 7/8
E.	Both arms extended over head	8-7/8	$\pm$ 3/4
F.	One arm over head, one hand in lap	8-5/8	$\pm$ 3/4
G.	Both arms extended laterally	8-1/8	$\pm$ 3/4
H.	One arm extended laterally, one hand in lap	8-3/8	$\pm$ 3/4
I.	Both arms extended posteriorly	8	$\pm$ 7/8
J.	Trunk flexed on thighs, arms extended forward	15-1/8	$\pm$ 1-1/8
K.	Trunk flexed on thighs, arms down	14-15/16	$\pm$ 1-5/8

TABLE 2

POSITION OF MAN'S C.G. ALONG ROLL AXIS FOR VARIOUS BODY POSITIONS (SITTING BACK ERECT, SEAT 90° TO BACK, LEGS 50° TO THIGHS)

	BODY POSITION	LOCATION OF AV. C. G. (IN.)	HORIZONTAL RANGE FOR SUBJECT (IN.)
A.	One hand on stick control, one on control at side of seat	7-3/4	$\pm$ 7/8
B.	One hand on overhead control, one on control at side of seat	8	$\pm$ 3/4
C.	Both hands on overhead control	8-1/2	$\pm$ 1
D.	Trunk flexed on thighs, arms around knees	13-3/8	$\pm$ 1

TABLE 3

POSITION OF MAN'S CG ALONG ROLL AXIS FOR VARIOUS BODY POSITIONS (SITTING BACK ERECT, SEAT 90° TO BACK, LEGS 110° TO THIGHS)

	BODY POSITION	LOCATION OF AV.C.G.(IN.)	HORIZONTAL RANGE FOR SUBJECT (IN.)
A.	One hand on stick control, one on control at side of seat	9-1/16	± 7/8
B.	One hand on overhead control, one on control at side of seat	9-5/16	± 7/8
C.	Both hands on overhead control	9-7/8	± 1-1/8

TABLE 4

DISPLACEMENT OF BODY C.G. ALONG PITCH AXIS(LATERAL MOVEMENTS)

	BODY POSITION	LOCATION OF AV.C.G.(IN.)	HORIZONTAL AND VERTICAL RANGE FOR SUBJECTS (IN.)
A.	Standing, body straight	10	± 7/8
B.	Head flexed to side	1/2	± 3/4
C.	One arm extended laterally	1/2	± 5/8
D.	One arm extended across chest	3/8	± 3/4
E.	Head and trunk in lateral flexion	1-3/4	± 3/4
F.	One leg abducted	1-1/2	± 3/4
G.	Maximum lateral movement of both legs	1-7/8	± 3/4
H.	All body parts moved laterally	4-5/8	± 1-3/8

3.3 ADDITION OF WEIGHTS TO THE BODY

The report studied the shift of the cg caused by the addition of various weights to the body. It was concluded that the displaced cg was in agreement with the displacement as determined by calculation.

In summary the analysis of the test data indicate that man is capable of shifting his cg roughly 11 1/2 inches toward the head, 10 inches toward the feet, 8 inches anteriorly, 4 1/2 posteriorly, and 4 1/2 inches laterally. Further, the shift of the cg accompanying the movement of all body parts in a given direction is not the sum of the shifts produced by moving each part separately.

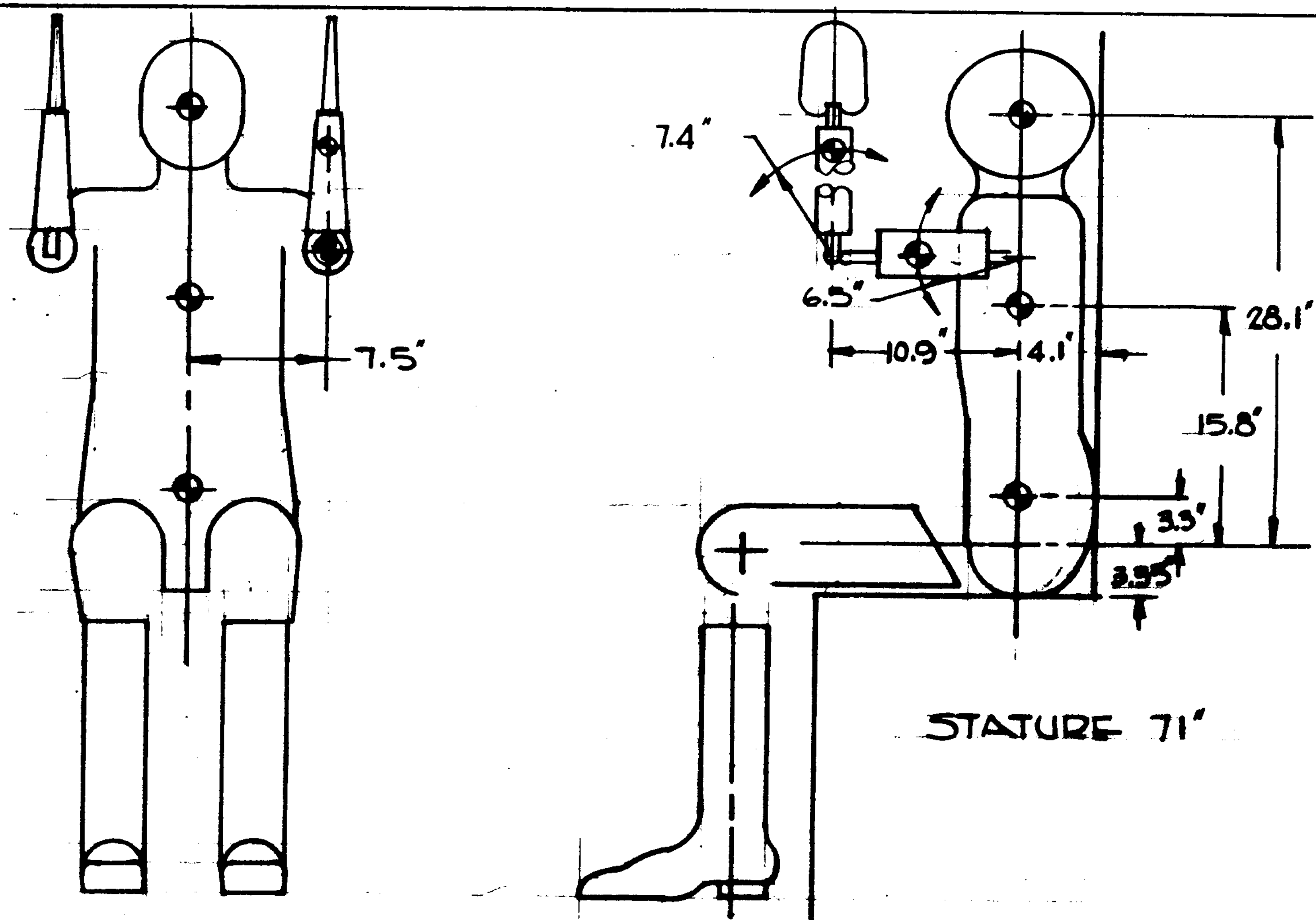
3.4 WEIGHT DISTRIBUTION AND CG LOCATION DATA

For purposes of this analysis it was necessary to make certain assumptions regarding the weight and centers of gravity of the man and the limbs. Certain work has been done along this line in the development of a suitable dummy of the standard airman. The following table represents data taken from Reference 2. These results are utilized in the calculation of the center of gravity shift for the various body positions.

TABLE 5
WEIGHT DISTRIBUTION OF DUMMY MEN
(Reference 2)

Component	% of Total Weight	Weight (lbs)
Head and Neck (Including a 3 1/2 lb ballast weight)	8.25	13.8
Upper Trunk (Including arm shackles, shoulders and a 6 lb ballast weight)	26.75	44.4
Lower Trunk (Including a 2 1/2 lb ballast weight)	14.5	24.0
Corset	1.05	1.7
Thighs (Including upper knee caps and shackles)	21.7	36.0
Legs and Feet (Including floating knee cap, lower knee cap and pin assy)	16.5	27.5
Upper Arms	5.45	9.0
Lower Arms and Hands	3.99	6.6
Suit (Including boots and mitts)	1.81	3.0
Totals	100	166

Figure 2 represents dimensional information regarding the center of gravity location for the various body parts. This data was taken from figures presented in Reference 2. The data represents a man whose stature is 71 inches. This data should be fairly representative of the location of the center of gravity for the average man. The effect of moving both arms forward and calculating the cg from the dimensional and weight information presented here resulted in a forward shift of the cg of 1.36 inches. The corresponding figure from Table 1 is 1.375 inches. The difference here is well within the testing accuracy.



LOCATION OF CG OF UPPER BODY COMPONENTS
DATA EXTRACTED FROM REFERENCE TWO

FIGURE 2

SECTION 4.0

DISPLACEMENT OF CG DUE TO SPACE SUIT LIMITATIONS

4.1 ITEMS OF EQUIPMENT AND NOMINAL CG SHIFT

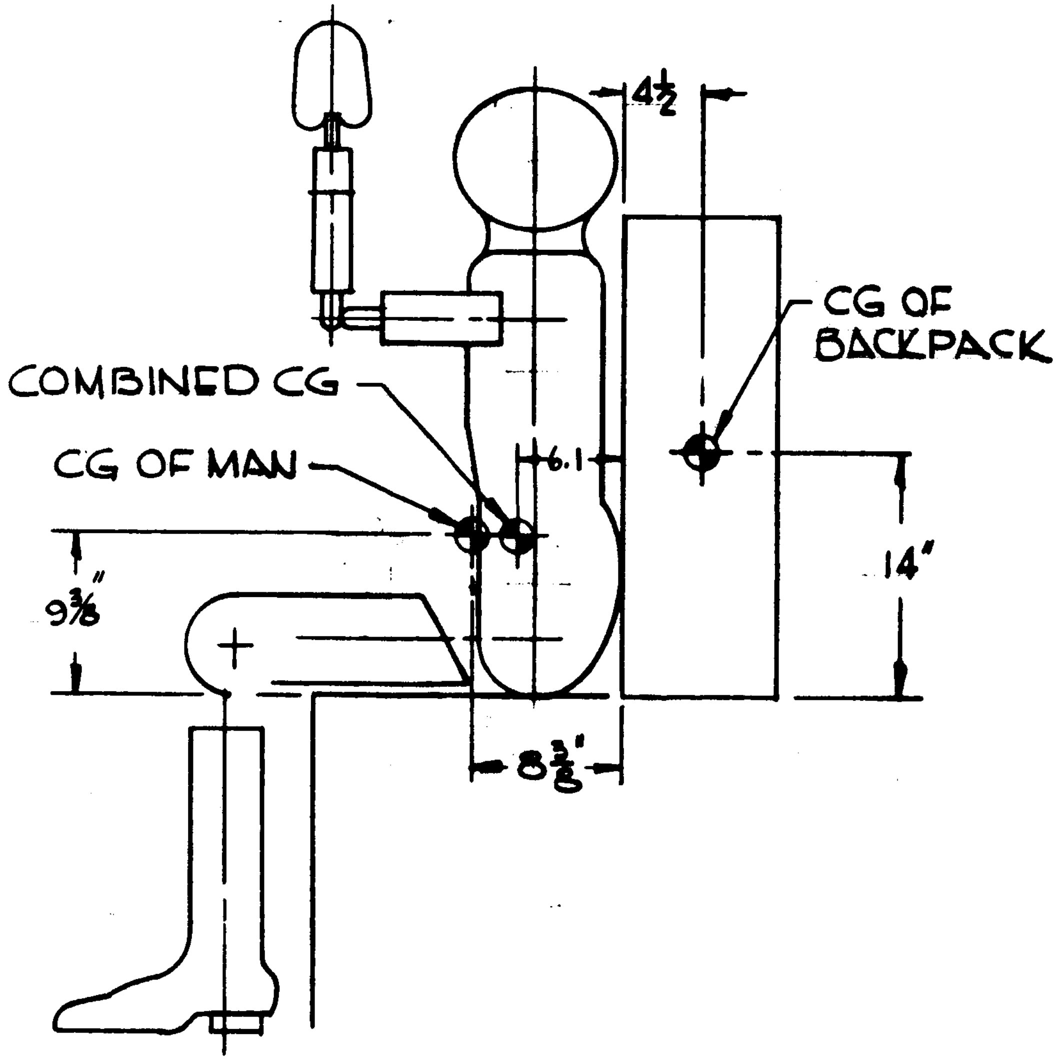
The elements of protective garments and life support equipment worn by the astronaut is shown in Table 5 (Reference 4).

TABLE 5
APOLLO SUIT AND PORTABLE LIFE SUPPORT SYSTEM WEIGHT

	Item	Weight (lbs)
1.	Torso Assembly	22
2.	Helmet with communications	8.5
3.	Liquid cooled garment	3.5
4.	Suit Maintenance Gear	6.0
5.	Portable Life Support System with battern and expendables	32.5
6.	PLSS Battery	3.5
7.	Expendables for PLSS	13
8.	Contingency	6
	Total	95

The torso assembly, the liquid cooled garment, and the helmet with communications (total weight 46 lbs.), may be considered as being equally distributed over the body of the astronaut, increasing his weight, but not modifying the cg location. The remaining three items, the battery, PLSS, and expendables are contained within a single envelope and mounted to the astronauts back. The weight of this package is 49 pounds and its approximate dimensions are 28 inches high, 9 inches deep, and 16 inches wide. The cg of this system is assumed to lie at the center of this envelope.

Figure 3 shows the relationship between the cg of a man sitting together with the cg of the backpack. The basic weight of an individual man is assumed at 185 pounds.



RELATIONSHIP BETWEEN CG OF THE ASTRONAUT AND CG OF THE BACKPACK

FIGURE 3

From this figure, the new $\overline{X}$, or horizontal dimension from the astronauts back to the new cg location is given by

$$X = \frac{(231)(8.375)-(49)(4.5)}{231 + 49}$$

$$= 6.1 \text{ inches}$$

The total weight is 280 pounds and the new cg is 6.1 inches from the reference line which is the back of the man.

There is nothing associated with the space suit equipment that will modify the lateral position of the cg, because of the assumption of symmetry.

4.2 CENTER OF GRAVITY SHIFT ACCOMPANYING SUITED ASTRONAUTS BODY MOVEMENT

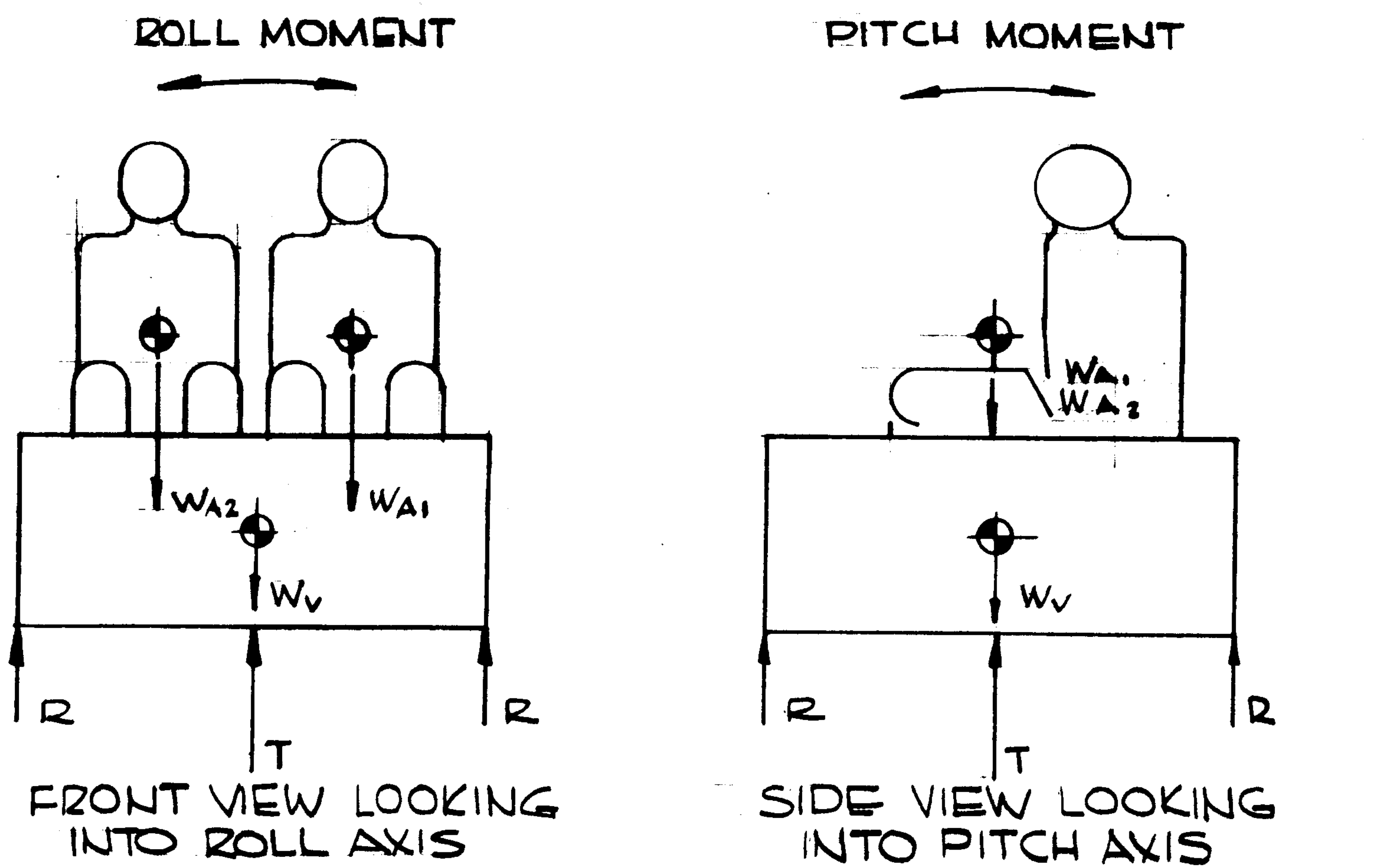
4.2.1 Shift Along the Roll Axis Due to Arm Motion

The astronaut's weight and cg location with respect to the vehicle axis is shown in Figure 4. From the side view, looking into the pitch axis it can be seen that the astronaut is positioned on the vehicle such that his nominal cg with backpack and space suit is on a line through the thrust axis of the vehicle. In Figure 5, the astronaut's weight is broken into three separate groups. These are the stationary body, weight of 258.15 pounds, the upper arms, weight 12.6 pounds, and the lower arms, weight 9.25 pounds. These weights were obtained by applying the percentage figures in Table 5 to the astronaut's weight. The dimensions to the cg of the body components were obtained from the information in Figure 2, together with the nominal location of the astronaut and backpack cg, which is 6.1 inches from the back.

From this figure the effect of both astronauts extending their arms forward results in a forward cg displacement of the entire vehicle of .5 inches. The extension of one astronaut's arms would, of course, halve this value.

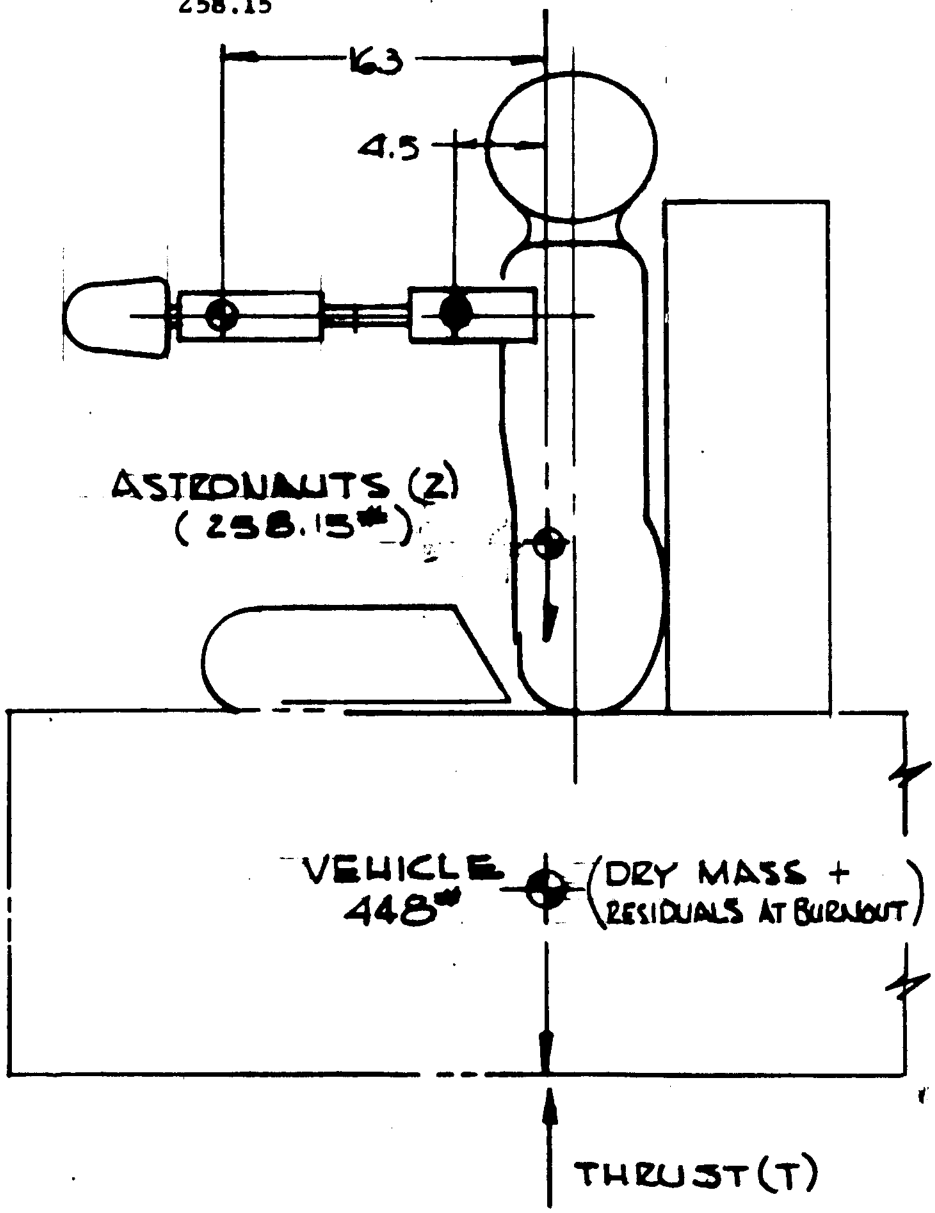
4.2.2 Shift Along the Roll Axis Due to Trunk Motion

The limitations of body motion due to the restraint of the pressurized suit and backpack must be considered before a value can



SUITED ASTRONAUTS' CG WITH RESPECT TO VEHICLE THRUST
FIGURE 4

Total weight of astronaut	280
Minus weight of attached gear	49
	231
Weight attributed to upper arms 5.45%	12.6
Weight attributed to lower arms 3.99%	9.25
Total weight displaced from c.g.	21.85
Weight remaining at original c.g.	258.15



EFFECT OF ARM EXTENSION ON CG OF VEHICLE FIGURE 5 be assigned to the effect of trunk movements. The values for cg shift given in Section 3.0 apply to a non space suited man and represent the maximum values under earth environment circumstances. It is unreasonable to expect that an astronaut in a pressurized space suit could achieve this amount of movement.

For the purpose of this study, it is assumed that the space suited astronaut will be able to achieve an angle of 30° forward from the vertical. This may represent the state of the art in the space suit development during the 1970-72 period.

Following the method utilized in Section 4.2.1, the location of the components of body weight in the assumed position are shown in relation to the nominal cg of the astronauts and the vehicle. This new position is illustrated in Figure 6.

The weight and location assigned to each of the components is given in Table 6.

TABLE 6
WEIGHT AND DIMENSIONAL INFORMATION FOR SUITED ASTRONAUT

Item	Percentage of Overall Lot	Assigned Weight (lbs)	Displacement Fwd (Inches)
Head, helmet and Communications	8.25	19	$28.1 \sin \theta$
Arms	9.44	21.85	$10.65 \sin \theta$
Upper Trunk	26.75	61.3	$15.8 \sin \theta$
Lower Trunk	14.5	32.5	$3.3 \sin \theta$
Backpack	Fixed	49	$8.6^2 + 11.2^2 \sin \theta$
Unperturbed portion	41.06	95.35	0

The vehicle cg shift is equal to the following expression:

$$\Delta\overline{X} = \sum_{i=1}^{n} W_i X_i / W_T$$

where W_T = Total weight of system (see Appendix 1)

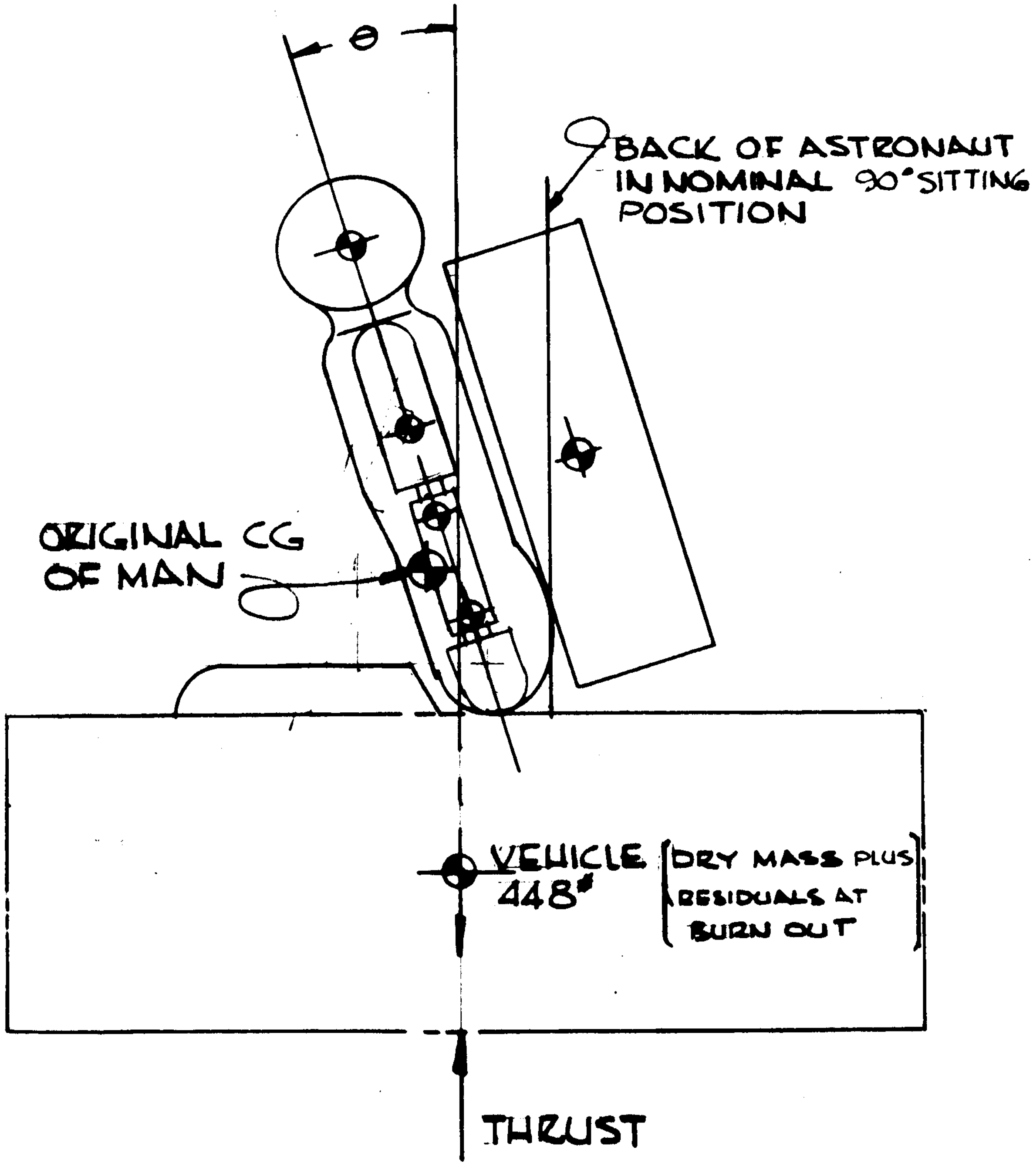

θ
BACK OF ASTRONAUT
IN NOMINAL 90° SITTING
POSITION
ORIGINAL CG
OF MAN
VEHICLE
448#
DRY MASS PLUS
RESIDUALS AT
BURN OUT
THRUST

FIGURE 6

Table 7 presents a tabulation of the effect of the astronauts leaning forward from an erect position. This analysis assumes the upper body remains in a straight line and the arms remain at the sides.

4.2.3 Shift of cg Along Pitch Axis Due to Arm Motion

The effect on an astronaut extending his arm to the side results in a small displacement of the center of gravity. By use of data from Figure 2 and corresponding weight allocations for the various body parts, the cg shift may be determined. In Figure 7, the weight and centers of gravity information for the extension of one arm to the side is indicated. From this diagram the cg shift for the vehicle is given by

$$\bar{y} = \frac{14\,(6.3) + 25.8\ (4.67)}{1008}$$

$$= .208 \text{ inches}$$

This value is doubled for both astronauts extending their arms in the same direction.

4.2.4 Shift of cg Along Pitch Axis Due to Trunk Motion

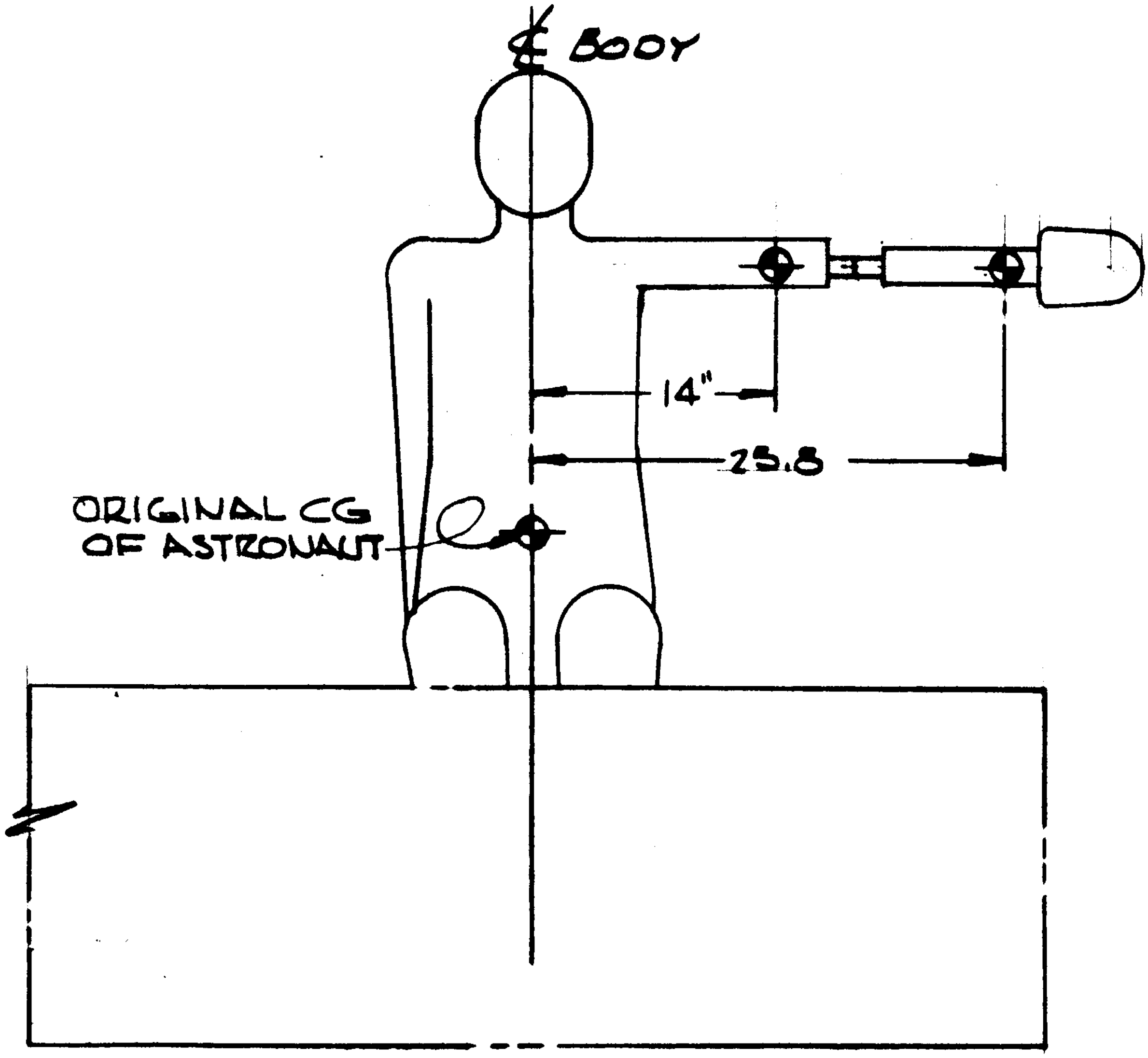
The various components of the body weight associated with the astronaut leaning sideways are indicated in Figure 8. This information is taken from Figure 2. In this diagram, the effect of movement of the lower arms may be neglected since the displacement is small. From this figure the effect of the leaning of one and two astronauts is related to the overall vehicle center of gravity shift. Table 8 presents the results for angles up to twenty degrees from the vehicle zenith axis.

TABLE 7

VEHICLE CG SHIFT VERSUS FORWARD ANGLE OF THE BODY

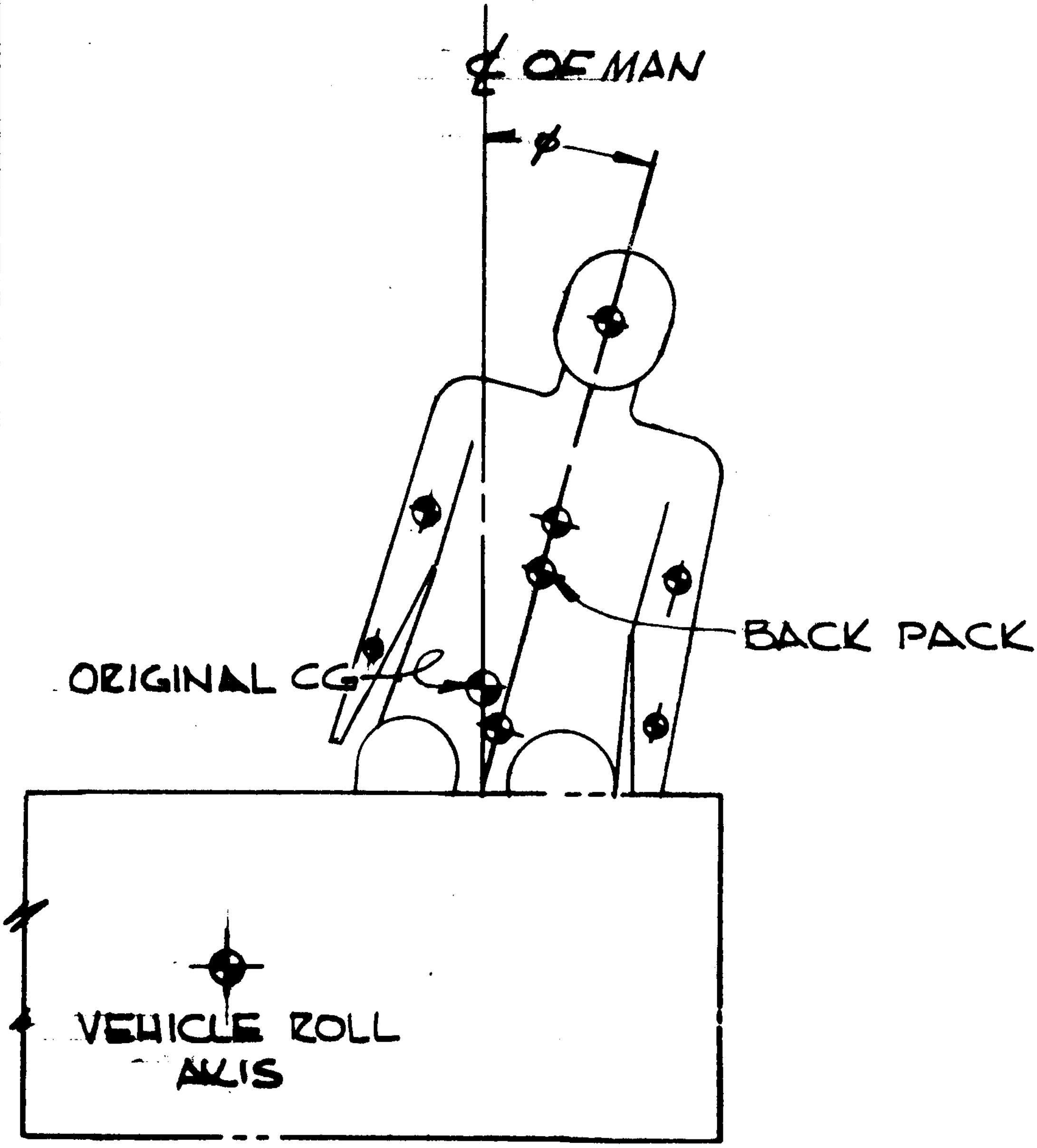
θ (degrees)	Body Component Displacement Multiplied by Body Component Weight				
	Head	Arms	Upper Trunk	Lower Trunk	Back Pack
5	46.6	20.2	84.2	9.6	10.2
10	92.8	40.4	168	19.1	119.5
15	138	60.1	250	28.5	178.5
20	182	79.6	331	37.8	236
25	225	98.1	408	46.5	291
30	267	117.4	494	55.2	345

θ (degrees)	$W X_i$	Vehicle C.G. Shift	
		One Astronaut	Two Astronauts
5	240.8	.238	.477
10	439.8	.436	.872
15	655.1	.65	1.3
20	866.4	.86	1.72
25	1068.6	1.06	2.12
30	1279.6	1.27	2.54



EFFECT OF ARM(SIDE)EXTENSION
ON CG OF VEHICLE

FIGURE 7



EFFECTS OF LEANING SIDEWAYS
IN CG SHIFT

FIGURE 8

TABLE 8

VEHICLE CG SHIFT ALONG PITCH AXIS DUE TO TRUNK MOTION

θ Degrees	Sin θ	Component Displacement Multiplied by Component Weight					$\sum w_i y_i$	System c.g. Shift (Inches)	
		Head	Upper Trunk	Back Pack	Lower Trunk	Upper Arms		1 Astronaut	2 Astronauts
5	.087	46.6	84.2	47.8	9.6	14.3	202.5	.201	.402
10	.175	92.8	168	95.5	19.1	28.7	404.1	.4	.8
15	.268	138	250	147	28.5	31.9	595.4	.591	1.18
20	.342	182	331	187	37.8	56.7	794.5	.787	1.58

SECTION 5

EFFECTS OF CG SHIFT ON VEHICLE ATTITUDE CONTROL SYSTEM

The results of the analysis in Section 4.0 indicates that the astronaut is capable of shifting the vehicle center of gravity by moving his arms or his trunk. Table 9 summarizes this data.

TABLE 9
VEHICLE CENTER OF GRAVITY SHIFT BY ASTRONAUT BODY POSITION

Position	Vehicle cg Shift	
	Forward (Inches)	Laterally (Inches)
Both arms forward (two astronauts)	.5	
Both arms forward (one astronaut)	.25	
Trunk forward 10° (one astronaut)	.436	
Trunk forward 30° (one astronaut)	1.27	
Trunk forward 10° (two astronauts)	.872	
Trunk forward 30° (two astronauts)	2.54	
One arm extended (one astronaut)		.208
One arm extended (two astronauts)		.416
Trunk tilted 10° sideways (one astronaut)		.40
Trunk tilted 20° sideways (one astronaut)		.787
Trunk tilted 10° sideways (two astronauts)		.80
Trunk tilted 20° sideways (two astronauts)		1.58

The effect of the relocation of the cg off the thrust axis is to generate an overturning moment. This moment is equal to the total weight of the vehicle multiplied by the amount of the shift. The moment is equal to

$$M = \frac{\Delta x}{12} (1008) \text{ ft-lbs} = 84 (\Delta x) \text{ ft-lbs}$$

This moment is reduced to 1/6 of this value in a lunar gravitational field.

The angular acceleration which this moment imparts to the vehicle is given by:

$$\ddot{\theta} = 1/6 \frac{M}{I}$$

where $\ddot{\theta}$ = angular acceleration
I = vehicle inertia

For the lunar vehicle near burn out, $I_{xx} \approx I_{yy} \approx I_{zz} = 100$ slug ft^2.

$$\ddot{\theta} = 1/6 \frac{M}{100} (57)$$

$$\ddot{\theta} = 1/6 (.84)(\Delta x)(57) = 8 (\Delta x)\ ^\circ/\text{sec}^2$$

Table 10 gives a tabulation of angular acceleration for various levels of cg shift.

TABLE 10
ANGULAR ACCELERATION FOR VARIOUS CG SHIFTS

CG Shift Inches	Angular Acceleration ($^\circ$/sec^2)	Overturning Moment (ft-lbs)
.1	.8	1.4
.4	3.2	5.6
.6	4.2	8.4
1.0	8.0	14.0
2.0	16.0	28.0

SECTION 6.0

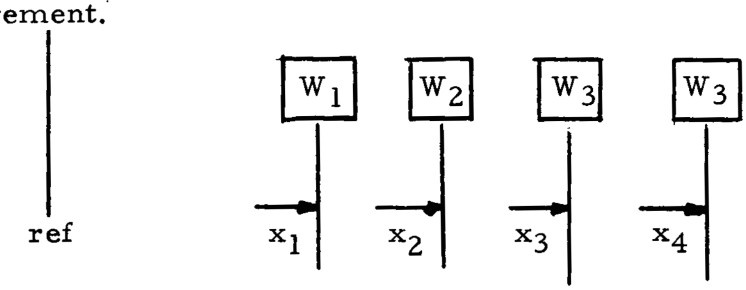
CONCLUSIONS

The moment capability of the attitude control system is listed in Reference 1 as 35 lb. ft. for the Pitch Axis and 48.3 lb. ft. for the Roll Axis. This corresponds to a cg shift of .208 ft. for the Pitch Axis and .278 ft. for the Roll Axis. The report in Reference 1 states that the reaction jets are sized to control a disturbance torque which is 40% of the control power available. Utilizing this 40% criteria the cg shift that the system can tolerate is 1 inch for the Pitch Axis and 1.33 inch for the Roll Axis.

The results of this report indicate that a suited astronaut can exceed this limitation through body motions, other sources of cg shift being neglected. This represents a potential problem area. The astronauts ability to move about must be suitably constrained or else the attitude control system capability must be increased.

APPENDIX 1

Simplified expression for center of gravity shift due to component weight movement.



In Figure 1, the weight W_3 is moved from x_3 to x_4. The original cg is

$$\bar{x}_1 = \frac{W_1x_1 + W_2x_2 + W_3x_3}{W_1 + W_2 + W_3}$$

The relocated cg is

$$\bar{x}_2 = \frac{W_1x_1 + W_1x_2 + W_3x_3 - W_3x_3 + W_4x_4}{W_1 + W_2 + W_3}$$

which reduces to

$$\bar{x}_2 = \bar{x}_1 - \frac{W_3 \ x}{W_1 + W_2 + W_4}$$

Thus the cg shift is given by the component weight multiplied by the displacement divided by the total weight.

In general, $\Delta \bar{x} = \sum_{i=1}^{n} (W_i)(\Delta x_i) \Big/ W_T$ where W_T is overall weight.

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